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Multi-Color Photometry of the 2001 Superoutburst of WZ Sagittae

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ABSTRACT

We present the results of U-band and multi-color photometry during the 2001 superoutburst of WZ Sagittae. Our 10 nights of U-band photometry span the time interval from HJD 2452118 to 2452197 while our multi-color observations range from HJD 2452115 to 2452197. The U-band light curves are generally in agreement with other datasets obtained during the superoutburst showing highly modulated light early on, rebrightenings, and superhumps of similar shape and period (except during the rebrightening peak). One of our multi-color datasets fortuitously covers the first rebrightening and allows determination of the accretion disk color temperature before, during, and after the event. It is seen that the rebrightening is a change from a neutral disk (T∼7000K) to an ionized disk (T∼10000K) and back again. We develop a simple limit cycle model for this behavior which approximately predicts the semi-periodic timescale observed for the rebrightenings. We discuss our results in relation to accretion disk structure during superoutburst.

1. Introduction

WZ Sagittae is often considered the quintessential short period dwarf nova, especially for the class of objects called TOADS (Tremendous Outburst Amplitude Dwarf novae) which only have infrequent (yearly to decadal) superoutbursts (see Howell et al., 1995). WZ Sagittae is the brightest TOAD at minimum light (V=15.0), has the longest intra-outburst timescale (20-30 years), is the closest cataclysmic variable at 43.5 pc (Harrison et al., 2004), and has one of the shortest known orbital periods (P=81.6 min).

Study of dwarf novae during superoutburst provide astronomers with information ranging from the binary orbital period to a mass estimate for the secondary star via detailed study of the period, shape, and time scale of so-called superhumps visible in the light curves (e.g., Patterson et al., 2002 and references therein). Superhumps are periodic hump-like modulations observed in the photometric signature of the star during superoutburst with periods a few percent different from that of the binary orbital period. Additionally, the morphology of the superoutburst itself, often combined with multi-wavelength observations, can provide a direct measurement of the properties of the accretion disk and its behavior during the outburst (e.g., Howell et al., 1999).

Superoutbursts are often observed via world-wide observer networks with the majority of observations being made by small telescopes and amateur astronomers. Their telescopes are generally equipped with CCDs and observations are routinely obtained in “white light”. These unfiltered CCD images, when convolved with quantum efficiencies typical of the CCDs used, produce “pink light” observations. Only one TOAD, WX Cet, has multi-color photometric superoutburst observations (Howell et al., 2002) from which the authors concluded that the superhump period was grey in the optical and the observed period agreed with that determined solely by white light observations.

During August 2001, WZ Sagittae erupted in superoutburst 11 years prior to prediction and was observed by essentially every professional telescope available (both on the ground and in orbit) in addition to hundreds of amateurs around the world. A summary of the massive ground-based observational campaign obtaining CCD photometric observations and a detailed interpretation of their meaning is presented in Patterson et al. (2002).

During this same time period, we collected multi-color photometric measurements throughout the superoutburst as well as the first set of U-band time series observations for WZ Sagittae during a superoutburst. We present these data and interpret them in relation to other photometric observations of WZ Sagittae during superoutburst as well as relating the observations to accretion disk structure and the formation and cause of the semi-periodic rebrightenings.

2. Observations

Photometric observations were obtained as time series data sets in U-band and as single measurements in U, B, V, R, and I. Tables 1 and 2 present observing logs of the U and multi-color observations respectively.

2.1. *U*-Band Observations

Ten nights of U-band photometry were obtained at the US Naval Observatory's Flagstaff Station (NOFS) between the beginning of WZ Sagittae's superoutburst and its return to a normal minimum state. Observations were obtained on the 1.0-m telescope at NOFS using the SITe/Tektronix 1024x1024 CCD with an 11x11 arcmin field of view. The comparison stars listed in Henden and Landolt (2001) were used to set the nightly zero points (with star 2/C being the primary comparison) but no transformation to the standard system was performed. The NOFS U-band filter is similar to one suggested by Bessell (1995) which gives reasonable transformations for normal-colored stars. Since the same comparison star(s) were used for all time-series nights and the color difference between WZ Sge and the comparison star(s) is not extreme, the small transformation error involved in not transforming the data only results in a minor zeropoint adjustment ($\sim$0.02 mag), lost in the chaotic noise of the intrinsic variation of WZ Sge and not affecting the light curve analysis that follows. For each night, standard CCD bias subtraction and flat fielding were performed, followed by aperture photometry and differential photometry using the inhomogeneous ensemble photometry technique described in Honeycutt (1992).

Observations began on HJD 2452118 (the sixth day of the superoutburst) and ended on HJD 2452197, outburst day 85. The exposure times ranged from 20 to 60 seconds with time series durations from 0.8 hours to 7.4 hours. Table 1 lists the mean U magnitude and the duration of each time series.

2.2. *UBVRI* Observations

Multi-color photoelectric data were obtained for WZ Sagittae's superoutburst in U, B, V, R and I filters on the CTIO 1.5 meter telescope. Ten nights of data were collected beginning on HJD 2452115, day 4 of the superoutburst, and ending on HJD 2452197 or outburst day 85 (Table 2). These observations were tied to Landolt (1992) and provide two overlapping days (day 35 and 85) of data with the U-band observations from the Naval Observatory.

All the CTIO observations used a 14.0 arcsecond diameter diaphragm and from HJD 2452115 through 2452145, 10 second exposure times were used for all filters (resulting in tens of thousands of counts per integration) while the remaining observations used 40 second exposure times providing 10,000 counts in U and more in the remaining filters. The sky was photometric throughout the CTIO run (with the exception of marginally photometric conditions on HJD 2452194). All the observations were guided, thus WZ Sge remained centered in the diaphragm at all times and no contamination occurred from the close by (10" east) red companion star. The final transformed magnitude and color indices are better than one percent in all cases except U-B which is about ± 0.015.

In addition, seven sets of transformed multi-color photometric observations were obtained at the US Naval Observatory using the instrument and telescope setup described above. These are also listed in Table 2.

3. Analysis

3.1. U-Band Observations

Figures 1 and 2 present our U-band time series observations (except for the two short runs) and show a variety of structures and modulations. Observations from early in the outburst (day 6) show a well defined orbital modulation evident in similar light curves shown in Patterson et al. (2002, See their Fig. 2). Superhumps became evident on HJD 2452137 (around day 24/25) as seen in Figure 1 (lower panels). Superoutburst day 28 (HJD 2452140) in Figure 2 shows the most consistent superhump light curve peaking continuously at an approximate U magnitude of 12. Three nights later, on HJD 2452143 (outburst day 31) the light curve changed drastically as it dropped slightly (a few tenths) and with no evidence of superhumps. This particular light curve occurred at the peak of the first rebrightening (see discussion below). Forty days later (HJD 24521097) modulations returned to the light curve, essentially those typical of minimum light.

We searched for periodic behavior in each night's U-band observation using the phase dispersion minimization (PDM) routine of Stellingwerf (1978). Our results are presented in Table 3. Our errors for each determined period are fairly large (3 to 5 minutes) as each dataset is either rather short or the light curve contains non-periodic modulations with only outburst days 25 and 28 being good representations of familiar superhumps while outburst day 85 revealed a nearly minimum orbital period.. These two days also provide similar looking results and equal periods (within the statistics) compared with the pink light photometry presented in Patterson et al. (2002).

3.2. Multi-Color Photometry

Using our multi-color observations during the superoutburst, we can explore the physical state in the accretion disk. Figures 3 and 4 show the three epochs during the superoutburst for which we have multi-color data. We note here that during the superoutburst (V brighter than $/sim14$), the optically thick (boundary layer) accretion disk dominates the light in the (U) B through I bands (see Howell et al., 1999) while at minimum light, the white dwarf contributes nearly 50% of the optical flux (see Ciardi et al., 1998). The mass donor star has yet top be directly observed, even during quiescence in the IR (Howell et al., 2004). The left most panel in each plot covers days 3 to 5 of the superoutburst, the middle panel cover days 30 to 35 (the time interval of the first rebrightening), and the right most panel covers superoutburst days 78 to 88, essentially when the visual outburst was over (V$\sim$14.5, about 0.5 mag above minimum).

During an outburst, the emitted flux from an accretion disk is well represented by optically thick (blackbody) emission. This approximation scheme was first detailed and applied to accretion disks by la Dous (1989) in which each broad band color (i.e., U, B, etc.) provides a good approximation of the emissive flux for successively hotter to cooler (inner to outer) single temperature disk (see Fig. 2.8 in Warner 1995). More detailed accretion disk modeling, using stellar atmospheres and hydrodynamic codes has been applied today, but for our order of magnitude discussion below, the blackbody approximation is sufficient. Note that during (super)outburst, an optically thick approximation for the accretion disk emission is valid (see Fig. 3.32 in Warner 1995) but is generally invalid during quiescence, at least for the low mass transfer (short orbital period) CVs (see Fig. 2.33 in Warner 1995).

Using the above assumption that the accretion disk emission is incandescent (i.e., optically thick) during the early superoutburst (days 3 to at least 70), the photometric colors can supply us with color temperatures for the disk emitting regions as the outburst progresses. In the far right panel (near the end of the superoutburst), we can not be certain that the observed colors, at this time, can be attributed to optically thick material as WZ Sge's accretion disk at minimum light has optically thin components (see Mason et al., 2001) Table 4 lists our determined color temperatures within the two early time intervals under the assumption that the emitted light is from optically thick gas, that is, it can be modeled as blackbody emission.

Examination of the early multi-color observations shows that the U-B color became redder from superoutburst day 3 to 5, while the other colors remained fairly constant albeit being blue. The reason that U-B became redder is likely related to the diminished high temperature of the inner disk and boundary layer which rapidly drops early on in the superoutburst and this region becomes optically thin (see Howell et al., 1999).

The middle panels in Figs 3 & 4 show a very interesting time in the superoutburst as this time period spans, from start to finish, the first rebrightening. The peak of the first rebrightening occurred on superoutburst day 32.6 (HJD 24521043.6; see Patterson et al., 2002) the time when all of the colors (except U-B, see below) change to a much bluer (hotter color temperature) value. The entire first rebrightening is seen to start and end near V=12.7 with redder colors and a temperature near 6800-7500K. During the peak of the rebrightening at V=11.2, the colors are bluer and we see color temperatures of 9000-10000K (in B, V, and R) but only 7700K in R-I. The U-B color is bluer at rebrightening maximum but the temperatures derived from this color index are very high indeed and likely indicate that the emitting region may be fully ionized throughout the rebrightening. This being the case, we can no longer believe in the complete validity of a determined U-B color temperature derived from the assumption of optically thick gas. Howell et al. (1999) show that during early superoutburst, the inner disk regions are quite hot and optically thin (i.e., a central disk hole exists). The hot white dwarf surface and the boundary layer probably provide most of the U-band light during this time period.

Essentially all TOADs show a cooling wave effect during their superoutburst. This event is observed as a large drop in brightness near day 25-45 in their superoutburst light curve (e.g. Richter 1992). The source of this cooling wave dip in superoutburst light curves occurs near the inner accretion disk (Kuulkers et al., 1996). WZ Sagittae and EG Cnc before it, produced a number of semi-periodic rebrightenings during this “dip” time period in place of a single large dip. We note that the previous two superoutbursts of WZ Sagittae, unlike this one, show a single large cooling wave dip (Richter 1992; Patterson 1980) of total duration $\gtrsim$9 days (1946) and 19 days (1978) while the total length of the 12 rebrightenings in the 2001 superoutburst was 23 days. While of a longer duration, the “by eye” integral under all the rebrightenings in the 2001 superoutburst is nearly the same as the area in the single cooling dip during 1978. We note in Fig. 2, that at the start of the cooling wave dip (outburst day 27) no superhumps are present in the U-band. It is tempting to try to draw a conclusion that the 33 year interval up to the 1978 superoutburst produced a single large cooling wave dip while the shorter 21 year interval up to the 2001 superoutburst led to numerous rebrightenings during this same time period.

The cause of the drop in light output during the dip is a quenching of the disk outburst by a cooling (density) wave of mainly neutral material moving through the disk. If enough disk material is piled up ahead of the wave, it can cause a back pressure and thus reflect the cooling wave causing a rebrightening, thus ending the dip. It is assumed that these cooling wave dips are not seen (as dramatically at least) in normal dwarf novae outbursts as the amount of material involved in the outburst (moving through the disk) is too small. In order to see if a thermal limit cycle may be at work in the accretion disk and cause

the semi-periodic rebrightenings, we develop here a toy model. Based on our multi-color observations we see that the color temperature crosses the hydrogen ionization boundary during the rebrightening. The simple starting assumption for the rebrightening is that a volume of neutral hydrogen gas is heated to $\sim$10000K and becomes hotter and brighter (bluer) as well as soon becoming fully ionized. It then cools (mostly by line radiation with some expansion) and returns to neutral gas at which time it will be cooler and fainter.

During the first rebrightening, the color temperature derived for most of the disk (Table 4), is seen to oscillate from below the hydrogen ionization temperature to above it at the peak of the event. The R-I color is an exception and probably indicates that while the outer accretion disk temperature changes as well (higher during the peak) the outer disk never becomes fully ionized. The behavior of the colors and the derived color temperatures during this interval suggests that the accretion disk regions which participate in the general decline of the superoutburst (assuming pure hydrogen composition) start and end mainly neutral, but become ionized near the peak of the rebrightening. This type of behavior and the multiple rebrightenings lead us to suggest a model of the accretion disk during the rebrightenings which operates as a limit cycle.

4. Simple Limit Cycle Model

Since the rebrightenings are oscillatory with a "period" near 1.5 to 2 days (see Fig.1 in Patterson et al., 2002) we desired to determine if some characteristic timescale within the disk during superoutburst might cause such an effect.

We can establish the luminosity of the start (end) and peak of the first rebrightening during the superoutburst as we now know the distance to WZ Sagittae (43.5 pc, Harrison et al, 2004). Using the V magnitude and standard filter bandpass, we find the values to be (start & end) 8.0×10^{28} and (peak) 2.5×10^{30} ergs/sec respectively, in good agreement with the predicted superoutburst luminosity at this time based on the model presented in Howell et al. (1999). Using the luminosity and color temperature values before (and after) and during the rebrightening, we can calculate the radius of the assumed spherical optically thick emitting region. Taking average color temperature values from Table 4 to be T_{cool}=7000K and T_{hot}=10,000K respectively, the emitting region radii are then found to be $R_{cool}=2.15 \times 10^8$ cm and $R_{hot}=5.9 \times 10^8$ cm. These values are again in agreement with the emitting sizes determined for TOADs during superoutburst when allowing for a time period of $\sim$30 days past peak brightness (Howell et al., 1999). Note here that we have made use of the simplifying assumption that each broad band color provides an estimate of a single temperature for regions within the accretion disk. The true situation is complex

with a mix of temperatures, but since we do not resolve the accretion disk, our photometric measurements average over the entire accretion disk area (i.e., temperature structure) visible at each epoch, leading to a mean temperature estimate within each color.

The total cooling rate, G, in a gas can be expressed as

$$G = L_R + L_{FF} + L_C,$$

where R = radiative, FF = free-free, and C= collisional cooling (Osterbrock 1974, §3.7). Following this argument and taking typical values for number densities in TOAD accretion disks ($N_e \sim 10^{10}$ to 10^{14} cm^{-3}), assuming that each hydrogen atom will (eventually) lose near 13.6 eV (2.18×10^{-11} ergs) during the cooling process, and the participating disk volume is the spherical volume discussed above (we could use a cylinder here, V = $\pi\ R^2_{hot} h$ where h is set to $0.1R_{hot}$, but for our toy model the difference is of no consequence) we find that the effective cooling rate will be in the range of 2.2×10^{21} to 2.2×10^{25} ergs/sec. Integrating the Saha equation[1] as one crosses the ionized to neutral temperature boundary (noting that the cooling required to return to neutral conditions drops rapidly as the temperature drops) and using the assumed shrinking emitting volume, as R_{hot} changes to R_{cool}, we find that the cooling times required (over the range of likely disk densities and assuming the range of G above) range from a few hundred seconds (at the high density end) up to nearly 3 days for the low density values.

During the superoutburst, with a hotter expanded disk, we might expect the densities to be better represented by the lower density values. The time scale determined for these densities (a few days) matches well that of the nearly periodic 1.5-2 day rebrightenings observed in WZ Sge. Thus, our toy model may provide a natural mechanism for the limit cycle causing the rebrightenings; semi-periodic cooling wave - reflected heating wave oscillations causing some portion of the disk gas to modulate across the sharp temperature boundary between mainly neutral to mainly ionized hydrogen. The reason for a single cooling wave dip, or its replacement by semi-periodic rebrightenings, may be some change in the amount of material involved in the superoutburst and/or the local disk conditions at the time. Note that in WZ Sge the accretion disk radius is approximately equal to the diameter of Jupiter (see Fig. 12 in Skidmore et al., 2001) while the emitting regions determined above are Earth-sized, making our use of an assumed spherical emitting volume within the accretion disk fairly justified. This 10:1 emitting area relationship (disk to varying emitting region) does not seem out of

[1]The Saha equation, when solved for the ratio of ionized to total hydrogen, tells us that for densities near $N_e \sim 10^{12}$, HII/HI=0 at 6000K and below but reaches 1.0 by 12,000K. The 5000K range in between shows a sharp, non-linear rise from all neutral to all ionized with the halfway point (HII/HI=0.5) being near 6400K (for our low density limit) and near 9200K (for our high density limit).

line to be able to account for the ∼1 magnitude (2.5 times) rebrightenings.

5. Conclusion

We find that our U-band time series photometry generally agrees in light curve shape and period (both orbital modulations and superhumps) with the more detailed pink light results presented in Patterson et al. (2002). Our multi-color results show that the superoutburst has a blue nature to it early on (related to the high temperatures produced) and returns to a blue color in U-B and B-V near the end due to the emergence of the hot white dwarf. Additionally, we find that the rebrightenings appear to be a transition in a local disk volume from mostly neutral conditions to fully ionized gas and back. A toy model based on a cooling wave-temperature limit cycle provides a time scale consistent with observations.

Our limit cycle model is a subset of the typical dwarf nova accretion disk outburst limit cycle. Perhaps the hydrogen ionization limit cycle operates within accretion disks on various physical scale lengths leading to many different observed phenomena such as the semi-periodic modulations which we call disk rebrightenings. This type of cycle may also be the cause for the observed rapid outbursts in the ER UMa stars and similar type oscillations at late times in classical novae outbursts.

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Figure Captions

Fig. 1.— U-band time series light curves for WZ Sge during superoutburst days 6, 7, 24, and 25. Note the large orbital modulation in days 6 and 7 and the fully developed U-band superhumps on day 25. Both light curve features are in agreement with the observations presented in Patterson et al., (2002).

Fig. 2.— U-band time series light curves for WZ Sge during superoutburst days 27, 28, 31, and 85. Note the apparent weakening of the superhumps in the U-band on day 27 caused by a steep decline in the flux over the time series. This day started the cooling wave dip phase. Superoutburst day 31 (lower left panel) shows the U-band light curve at the peak of the first rebrightening during which time no superhumps are apparent. This is in contrast to the light curves presented in Figure 5 of Patterson et al. (2002), but see our Figure 4.

Fig. 3.— Our V, U-B and B-V photometry for three selected time regions during the superoutburst. The light curve shapes and V magnitude values are in agreement with previously published values. Note the first rebrightening shown in the middle panel. During the first rebrightening, the U-band light (mainly from the inner disk region which is likely to be optically thin at this time) does not participate in the red to blue color change observed in the other colors. This condition likely explains the lack of superhumps observed during this time interval (see Fig. 2). Note the blue color of WZ Sge both early in the superoutburst and during the late decline.

Fig. 4.— V-R, R-I, and V-I photometry for the same three time intervals presented in Figure 3. Note the blue color early on but a red (accretion disk dominated) color during the late decline. During the first rebrightening, we again note a significant red to blue color change. However, the R-I and V-I (due to the I value) color temperature does not reach that for full ionization during the rebrightening peak (See Table 4).

Table 1. U Band Time-Series Photometry

HJD(2452100+)	Outburst Day	Mean U Mag (Range)	Duration (hr)
18	6	8.25 (+/-.25)	2.88
19	7	8.45 (+/-.11)	3.12
36	24	10.09 (+/-.12)	4.08
37	25	10.28 (+/-.16)	5.04
38	26	–	0.840
39	27	12.1 (+.2/-.3)	7.44
40	28	12.26 (+.16/-.3)	7.20
43	31	10.65 (+.35/-.2)	6.72
52	40	11.15 (+/.15)	1.39
97	85	13.28 (+.12/-.18)	4.90

Table 2. Multi-Color Photometry

HJD(2452100+)	V	B-V	U-B	V-R	R-I	V-I	Observer[a]
15.6745	8.269	-0.137	-0.962	–	–	–	AL
15.6774	8.218	-0.134	-0.944	-0.009	-0.011	-0.023	AL
15.7310	8.315	-0.120	-0.922	-0.014	-0.027	-0.044	AL
16.6514	8.553	-0.104	-0.819	–	–	–	AL
16.6543	8.638	-0.088	-0.811	+0.001	+0.032	+0.027	AL
16.6578	8.741	-0.090	-0.878	+0.037	+0.031	+0.063	AL
16.6614	8.768	-0.116	-0.838	+0.002	+0.008	+0.006	AL
16.6650	8.772	-0.112	-0.833	-0.003	+0.008	+0.001	AL
16.6684	8.746	-0.105	-0.827	-0.021	-0.010	-0.035	AL
16.6720	8.661	-0.100	-0.807	-0.003	+0.016	+0.009	AL
16.6753	8.650	-0.092	-0.797	-0.002	+0.015	+0.009	AL
16.7421	8.706	-0.090	-0.802	-0.014	+0.003	-0.015	AL
16.7455	8.621	-0.106	-0.898	0.000	+0.009	+0.005	AL
16.7491	8.571	-0.107	-0.916	+0.001	+0.003	0.000	AL
16.7525	8.544	-0.111	-0.898	-0.014	-0.001	-0.020	AL
16.7559	8.487	-0.104	-0.900	-0.005	+0.004	-0.004	AL
16.7593	8.487	-0.107	-0.872	+0.011	+0.007	+0.013	AL
16.7628	8.555	-0.086	-0.818	+0.011	+0.020	+0.026	AL
16.7661	8.646	-0.077	-0.782	+0.015	+0.021	+0.030	AL
18.7611	8.977	-0.037	-0.691	-0.042	+0.055	+0.013	AH
37.9152	10.839	+0.121	-0.576	+0.034	+0.134	+0.168	AH
39.9312	12.914	+0.074	-0.934	+0.225	+0.261	+0.486	AH
42.6691	12.826	+0.267	-0.930	+0.249	+0.328	+0.579	AL
43.6181	11.213	+0.001	-0.871	+0.092	+0.101	+0.198	AL
43.6610	11.227	-0.002	-0.868	+0 089	+0.085	+0.180	AL
44.5794	12.120	+0.048	-0.871	+0.135	+0.189	+0.323	AL
44.5954	12.126	+0.042	-0.949	+0.130	+0.171	+0.300	AL
44.6533	12.136	+0.087	-0.797	+0.106	+0.126	+0.232	AH
44.6635	12.116	+0.069	-0.859	+0.142	+0.164	+0.305	AL
44.7306	12.216	+0.145	-0.790	+0.105	+0.221	+0.326	AH
45.5823	12.591	+0.283	-0.796	+0.243	+0.290	+0.528	AL

Table 2—Continued

HJD(2452100+)	V	B-V	U-B	V-R	R-I	V-I	Observer[a]
45.7501	11.792	+0.266	-0.544	+0.148	+0.209	+0.683	AH
53.8371	11.298	+0.087	-0.589	–	–	–	AH
91.5322	14.171	-0.064	-1.096	+0.188	+0.279	+0.474	AL
94.5353	14.221	-0.048	-1.125	+0.128	+0.189	+0.338	AL
95.5335	14.251	-0.084	-1.130	+0.173	+0.135	+0.329	AL
97.5263	14.236	-0.024	-1.140	+0.092	+0.194	+0.267	AL

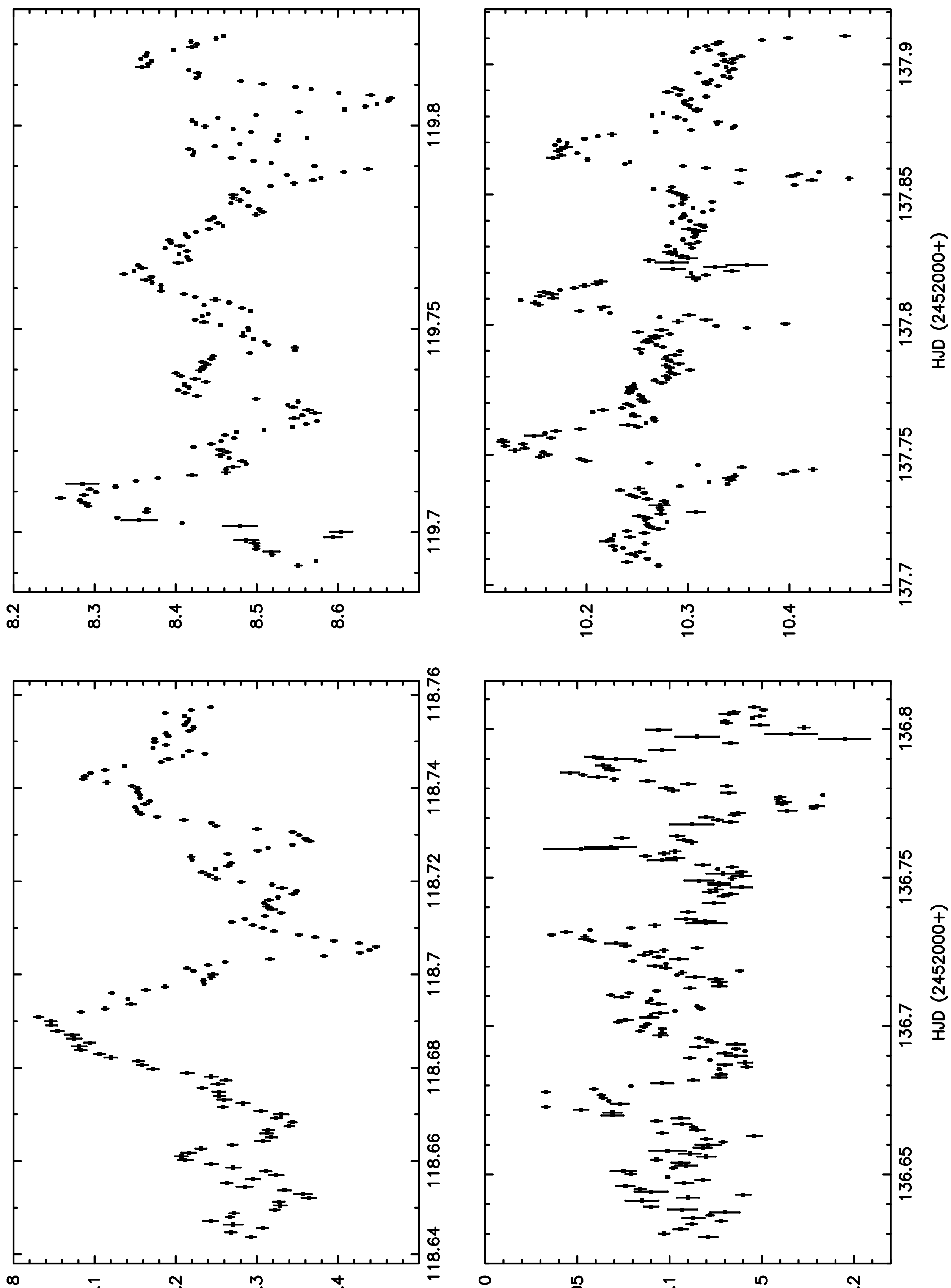
[a]AL = Arlo Landolt; AH = Arne Henden

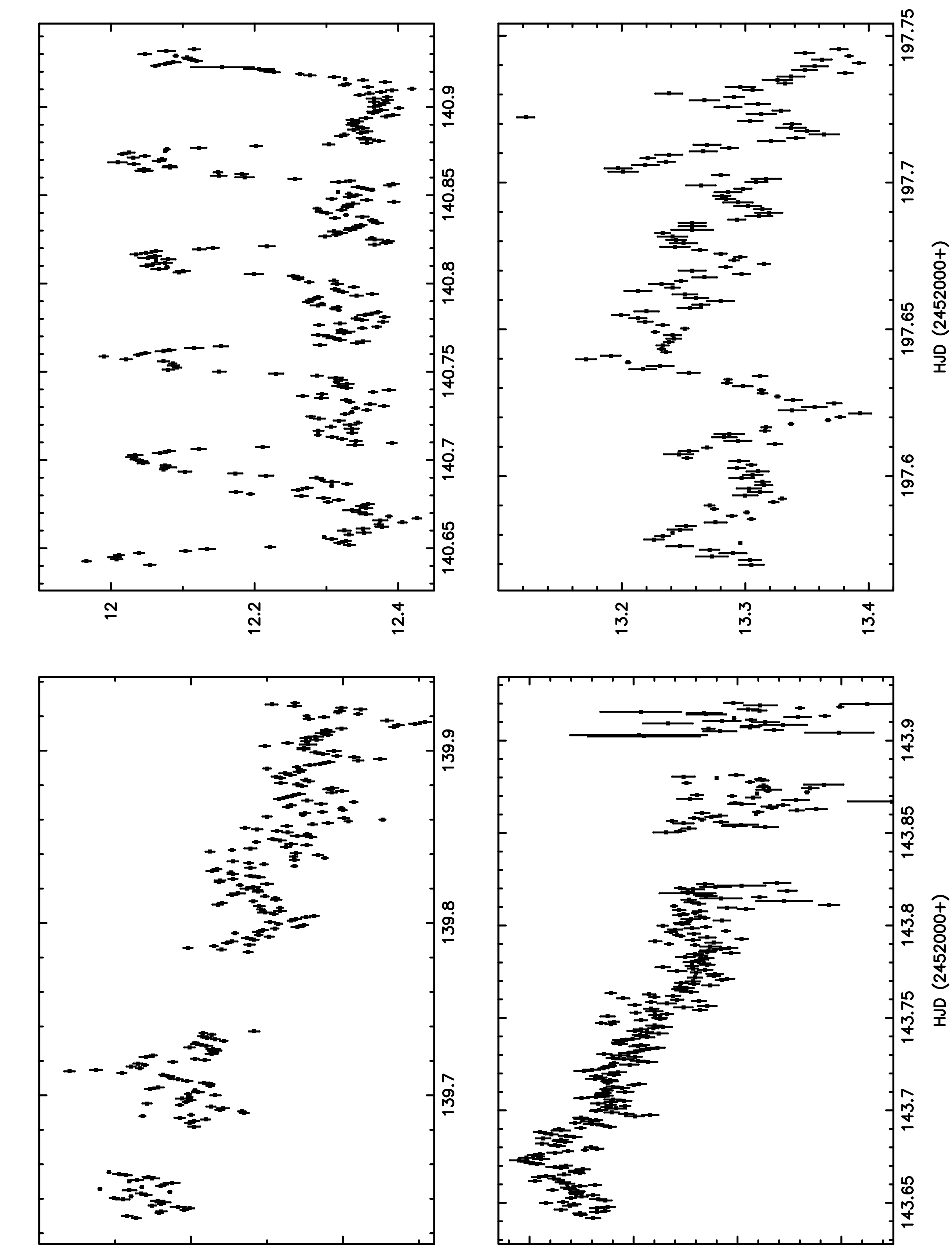
Table 3. Measured U Band Periods

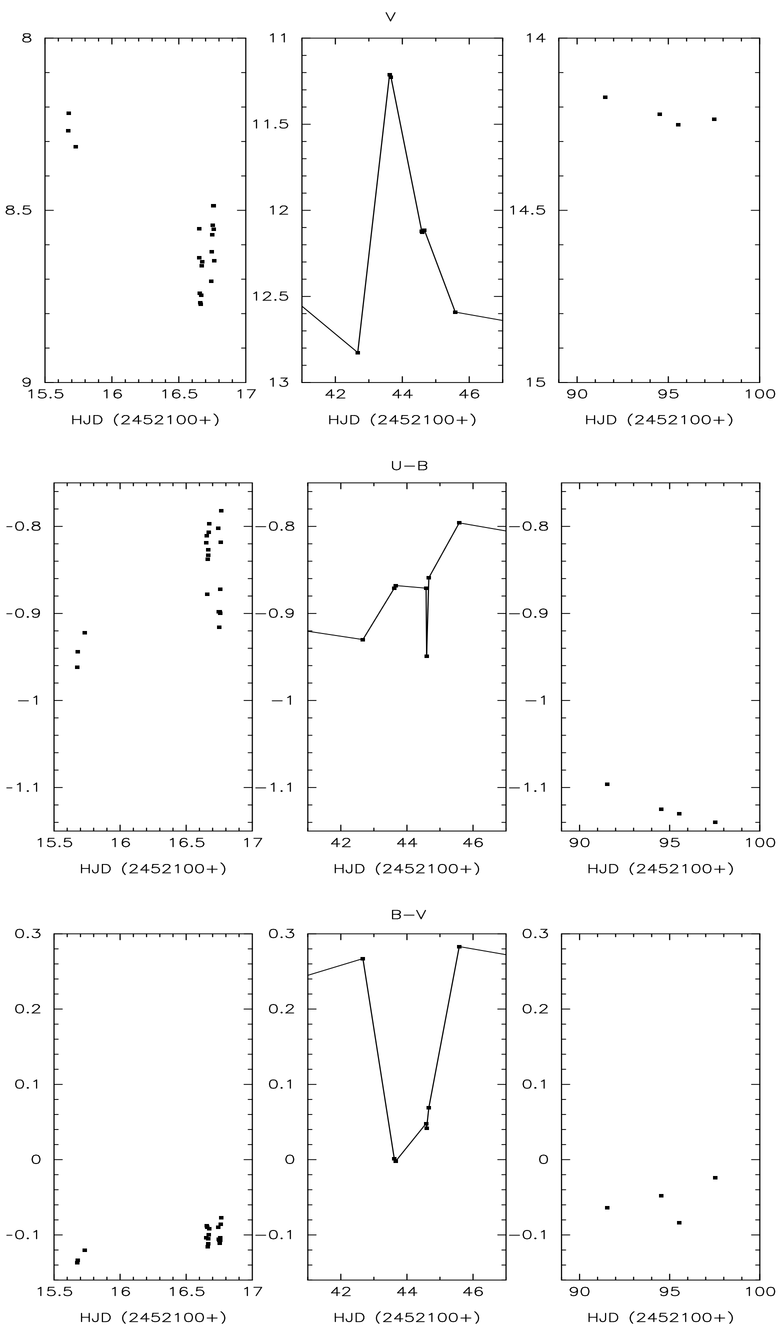
HJD(2452100+)	Outburst Day	Period (σ) (min)
18	6	78 +3.5/-13.1
19	7	82 +7.2/-9.6
36	24	none
37	25	81.6 +5.3/-5.1
38	26	none
39	27	85.2 +2.25/-7.78
40	28	82 +5.08/-6.3
43	31	none
52	40	none
97	85	86 +2.92/-3.5

Table 4. Color Temperatures (K)

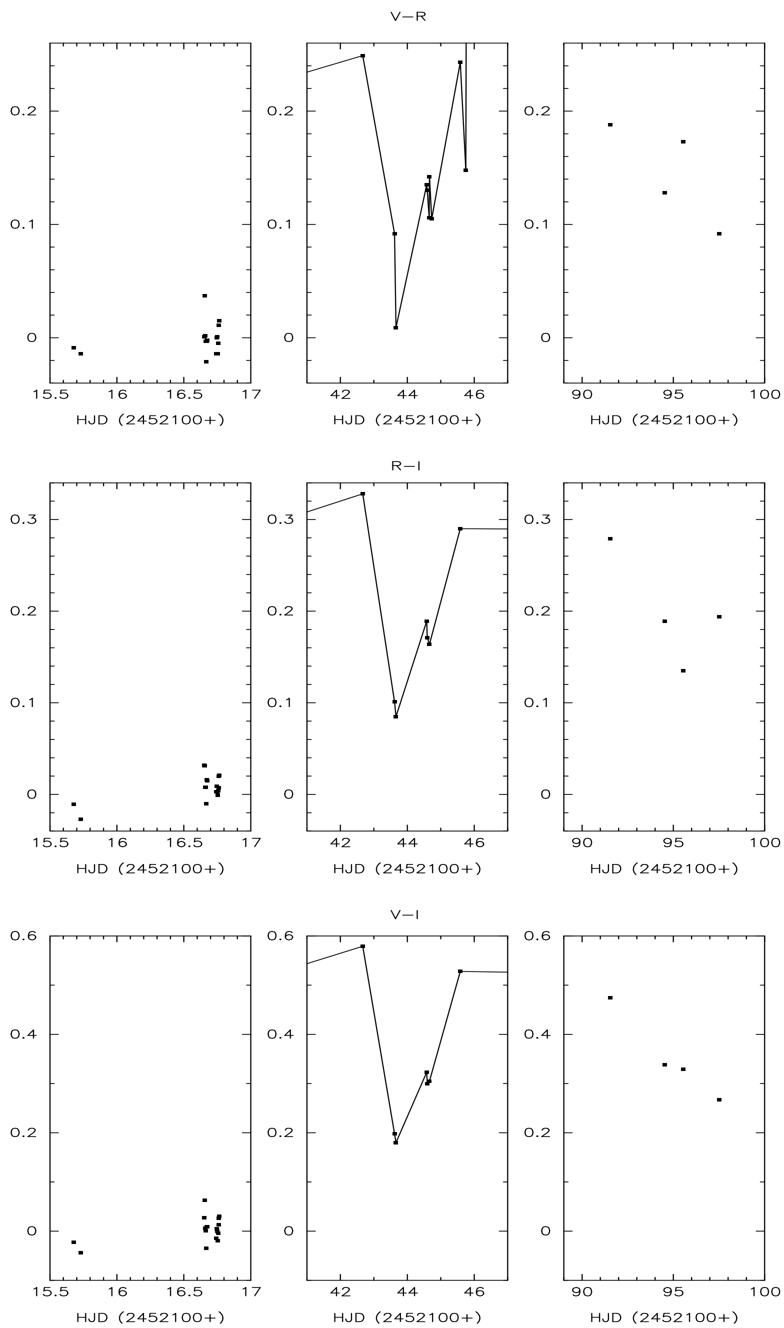
HJD interval (2452100+)	U-B	B-V	V-R	R-I	V-I
15.5-16	25000	–	–	–	–
16.5-17	19000	–	–	–	–
15.5-17	–	11400	10500	9500	9600
42-43	–	7500	7500	6250	6800
43-45	21000-25000	9000	9000-10500	7300-7700	7800-9000
45-46	19000	7500	7500	6450	6800


U
U
HJD (2452000+)
HJD (2452000+)


U
HJD (2452000+)
HJD (2452000+)
139.7
139.8
139.9
140.65
140.7
140.75
140.8
140.85
140.9
143.65
143.7
143.75
143.8
143.85
143.9
197.6
197.65
197.7
197.75
12
12.2
12.4
10.5
10.6
10.7
10.8
13.2
13.3
13.4



V
U−B
B−V
HJD (2452100+)


V−R
R−I
V−I
HJD (2452100+)
15.5
16
16.5
17
42
44
46
90
95
100
0.2
0.1
0
0.3
0.6
0.4